

# Fuse and Load Testing With Mid-Sized, High Energy Density Flux Compression Generators

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## Abstract

Compact Pulsed Power Systems (CPPSs) require power sources that are small in size yet can produce the necessary electrical energy required to drive a given load. Helical Flux Compression Generators (HFCGs) are attractive for single shot applications due to their rapid conversion of chemical energy to electrical energy. Mid-sized generators occupy little total volume ( $\sim 4,000\text{-cm}^3$  total with a compressible volume of  $\sim 300\text{-cm}^3$  in the present generator design), while the high explosives used in an HFCG provide an energy density of  $\sim 8,000\text{ MJ/m}^3$ . Consistent output current and energy gain from shot to shot are key variables in the ability of an HFCG to drive CPPSs effectively. An investigation into the practicality of using mid-sized HFCGs as the driver for single shot CPPSs is presented. Data and waveforms from generators fired into  $3\text{ }\mu\text{H}$  inductive loads are shown, with results measuring the generator's performance as a driver for an inductive energy storage (IES) system. Results are also shown from adding a power conditioning system to the output of the HFCG, where the measurements demonstrate the ability of an HFCG to drive high impedance loads. The effectiveness of a mid-sized HFCG as drivers for these systems will be evaluated.

## I. INTRODUCTION

HFCGs have been used as high current/high magnetic field sources since the 1950's. Systems powered solely by an HFCG can be limited by several factors. One factor is that small to mid-sized generators have been known to suffer from inconsistent output for successive shots [1]. One solution for this problem is to employ a construction technique which minimizes deviations in the generator characteristic parameters from one generator to the next. An HFCG design, fabrication technique and initial performance measure were outlined in [2] and [3], with the aim of increasing long term generator consistency. This paper provides more analysis on the consistency of generator performance for successive shots.

Another limitation of the HFCG is that the loads must possess low impedance or resistance characteristics in

order to maximize generator performance. Single stage HFCGs perform best when connected to inductive loads on the order of nanohenries and milliohms, or below. However, cascading HFCG stages has been successfully utilized to drive higher impedance loads [4]. For loads requiring high magnitude, short duration voltage pulses, such as a High Power Microwave (HPM) source, a power conditioning system must be used to couple the HFCG to the HPM load. A fuse opening switch along with pulse shaping techniques can be used as such a power conditioning system. Fuses used as opening switches have been around since at least the 1960's [5] and can provide the current interruption needed to provide the energy transfer to the HPM load. More recently, exploding wire fuses have been the subject of research [6], with a goal of tailoring the output of an HFCG to certain loads. Presented here are data and waveforms taken from HFCGs fired into energy storage inductors ( $1$  and  $3\text{ }\mu\text{H}$ ). A fuse opening switch coupling the HFCG to a  $20\text{ }\Omega$  resistive load is added, with data and waveforms shown for this system. Analysis and conclusions will highlight the characteristic performance of the HFCG as an IES driver, as well as the performance of the power conditioning system.

## II. EXPERIMENTAL OVERVIEW

Texas Tech University has an off-campus research facility used for explosives testing. Recording setups are placed in copper-mesh screen-rooms to help eliminate electro-magnetic interference. The overall setup has four main components: the HFCG, energy storage inductor, power conditioning system and the diagnostic- recording setups, each of which is described in the following.

### A. HFCG

The HFCG used for these experiments is dual-staged generator which employs a dynamic transformer as the energy seeding mechanism for the cascaded generator stages.

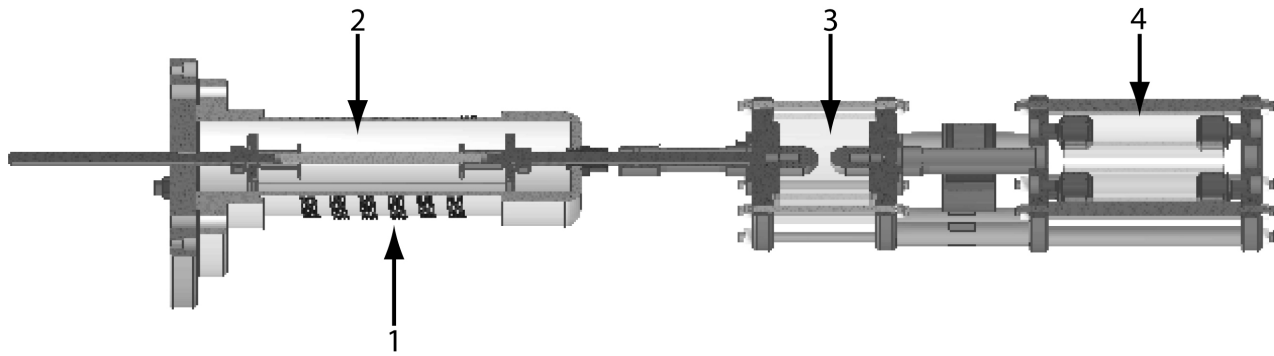


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**Figure 1.** Sectional View of Power Conditioning Assembly: 1.Energy Storage Inductor 2.Exploding Wire Fuse 3.Peaking Gap 4.Resistive Load

The dual stage design is necessary for the generator to amplify energy into relatively high inductances (i.e. in the micro-henry range). The first dynamic transformer, which couples the seed energy source to the first stage, is used to provide the initial flux to the generator. The first stage amplifies current into an inductive load ( $\sim 400$  nH) which also serves as the primary for the second stage dynamic transformer. The second dynamic transformer steps up the voltage from the primary to secondary windings, which allows the second stage to amplify current into higher inductance loads. The technique of seeding flux with a dynamic transformers helps to reduce ohmic heating in the helix wires during the energy seeding process.

The generator occupies a total volume of  $\sim 4000\text{-cm}^3$ , with an active volume of  $300\text{-cm}^3$ , and an armature expansion ratio of 2:1. The 30-cm long T6061 annealed aluminum armature holds 410 g of C4 high explosive. Refer to [2] or [3] for a more detailed description of the HFCG design.

### B. IES Inductors

The energy storage inductors (1 and 3  $\mu\text{H}$ ) are single layer coils and wound with a conductor cross section corresponding to at least three 12 AWG insulated wires in parallel. Initially, all (i.e. the first thirteen) generators were fired with the IES placed inside the detonation chamber, such that a new inductor had to be wound for each shot. In an effort to reduce fabrication and material costs, as well as to view any activity at the IES, the inductors were moved outside of the detonation chamber and connected to the HFCG output via a low inductance coaxial cable ( $\sim 200$  nH and  $\sim 22$  m $\Omega$  for a 1.2-m length of cable). The HFCG performance was measured by the current and energy amplification levels when fired into 3  $\mu\text{H}$  loads. Seven generators were also fired into 1  $\mu\text{H}$  loads and their performance was measured for comparison with the 3  $\mu\text{H}$  energy storage inductors. When measured with an LCR meter at 400 kHz, the 3  $\mu\text{H}$  and 1  $\mu\text{H}$  loads showed an ohmic resistance of  $\sim 100$  m $\Omega$  and  $\sim 20$  m $\Omega$ , respectively.

### C. Power Conditioning System

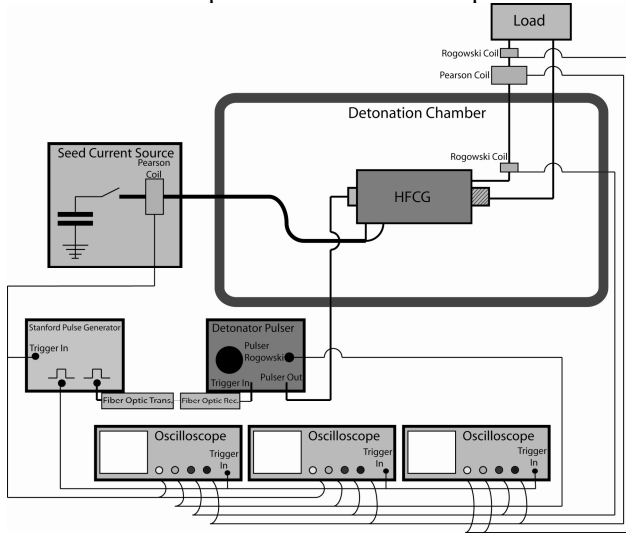
The power conditioning system consists of three main components: the energy storage inductor, fuse opening switch and peaking gap connected to the resistive load, see Fig. 1. The energy storage inductor has a value of 3  $\mu\text{H}$ , with the fuse opening switch connected in series with the inductor. Annealed gold wire with a diameter of 0.127-mm serves as the fuse conductors. The gold wire is wound between two gear plates, with electric field shaping rings attached to each gear plate. The amount of wire wound in the fuse can be varied depending on the desired fuse opening current magnitude. The fuse used for the data shown in this paper contained 14 gold wire conductors, with a total fuse cross sectional area of  $0.19\text{-mm}^2$  and a length of 239-mm. The assembled fuse is mounted inside a pressure sealed 114-mm diameter PVC vessel. The fuse pressure vessel also serves as the mandrel for the energy storage inductor. The fuse vessel is pressurized with  $\text{SF}_6$  as a quenching medium, to  $\sim 80$  psig, which is the minimum pressure in which re-strike did not occur in fuses of similar design, according to [6]. When the fuse opens, the potential across the peaking gap becomes  $L_{\text{storage}} * dI/dt$ . The peaking gap is housed in a 114-mm diameter acrylic tubing with 10-mm wall thickness and sandwiched between two brass plates. The electrode distance, as well as the pressure within the gap, is adjustable, allowing the gap hold-off voltage to be varied with the expected output voltage. When the gap breaks down, the voltage is seen at the resistive load, which consists of four 80  $\Omega$  water resistors in parallel. The lower potential terminals of the water resistors are connected to a brass plate which in turn is connected to earth ground. Voltage across the resistive load is measured with a custom fabricated capacitive voltage divider.

### D. Experimental Setup

As noted before, the first 13 tests fired generators with the IES loads placed inside of the chamber, whereas Fig. 2 represents the experimental setup with the load placed outside the chamber. A capacitive discharge source is triggered manually and the seeding current is established in the primary of the first stage dynamic transformer. A Pearson current monitor transmits the seeding current magnitude to a Stanford pulse generator and



oscilloscopes. When the signal level from the Pearson monitor reaches a set level, the pulse generator triggers both the detonator pulser and the oscilloscopes.



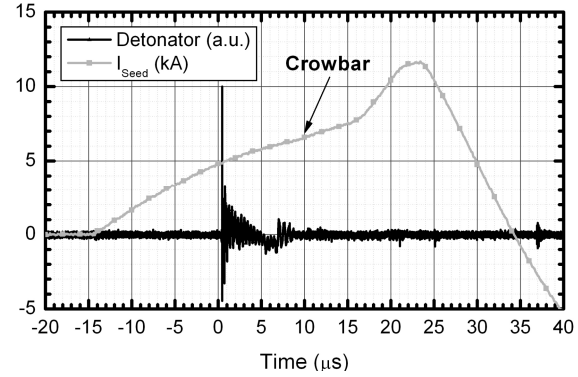
**Figure 2.** Experimental Setup for HFCG Testing

The pulse generator and the detonator pulser are isolated from each other through a fiber optic transmitter/receiver system for noise reduction purposes. The detonator pulser initiates the HFCG high explosive detonator and the generator run time begins. Pearson current monitors and custom fabricated Rogowski coils are the primary diagnostics used to measure output current and current derivative. Voltage across the IES and resistive load are calculated from  $L_{storage} * dI/dt$  and measured by capacitive high voltage probes, respectively. Three Agilent 500 MHz oscilloscopes are used to capture data, and each diagnostic is connected to at least two oscilloscope channels for redundancy and waveform scaling.

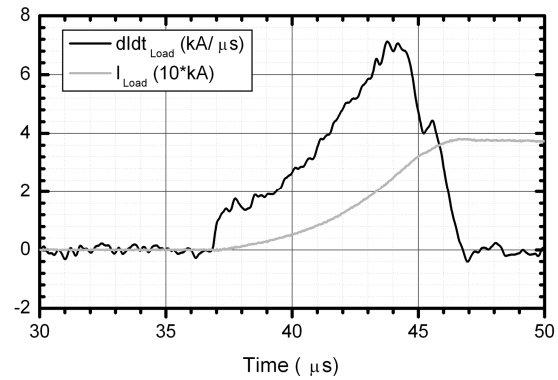
### III. EXPERIMENTAL RESULTS

To date, 23 generators have been fired into IES loads, and 5 have been fired into a power conditioning system (one shot shown here, four others shown in [7]). The seeding energy is calculated by examining the detonator and seed current waveforms. There is approximately a 10  $\mu s$  delay between detonator initiation, at  $t = 0$ , and crowbar, see Fig. 3. Crowbar can be identified on the waveform as the slight change in slope roughly 10  $\mu s$  after the detonator initiates. The current magnitude at the time of crowbar is used to calculate the seed energy through  $\frac{1}{2} * L_{seed} * I_{seed}^2$ . From this waveform, the current magnitude at the time of crowbar is 6.7 kA, giving a seed energy of 137 J with a dynamic transformer primary inductance value of 6.1  $\mu H$ . The measured current maximum was 38 kA, see Fig. 4. Using  $\frac{1}{2} * L_{Load} * I_{Load}^2$ , the total energy stored in the load was 2,000 J with a load inductance of 2.8  $\mu H$ , which results in an energy amplification of  $\sim 15$ . The voltage across the load inductor was calculated at  $\sim 21$  kV. Note that the waveforms are

produced from an HFCG fired into the IES load placed outside the detonation chamber and connected to the HFCG with a low inductance cable.



**Figure 3.** Seeding current and detonator waveforms

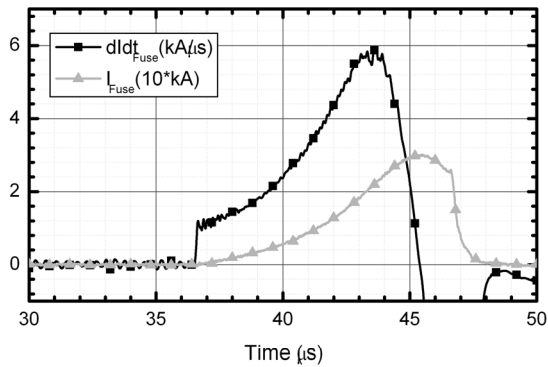


**Figure 4.** HFCG output  $dI/dt$  and current waveforms into high impedance load

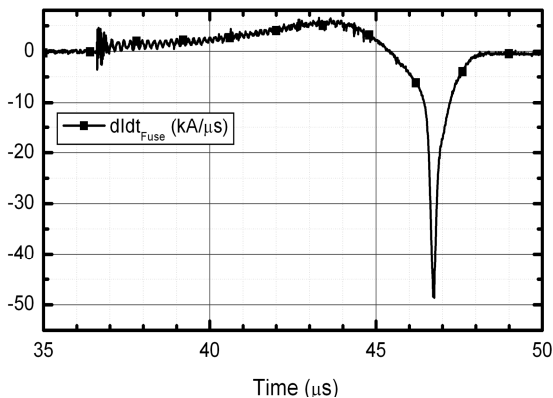
There were expected changes in performance between those HFCGs fired with the load located inside the chamber, and those fired with the load located outside the chamber, due to the added inductance and resistance of the connection cable (20% and 7% added inductance, 95% and 22% added resistance to the 1 and 3  $\mu H$  loads, respectively). Even with these performance changes, this HFCG design was consistently able to produce output currents in the range of 30-45 kA for 3  $\mu H$  loads and 60-80 kA for 1  $\mu H$  loads. Output energies ranged from 1,300-3,000 J for both load inductance values.

When the power conditioning system was added to the output of the HFCG, Fig. 5 shows that the fuse broke at approximately the peak of the HFCG output,  $\sim 6$  kA/ $\mu s$ , which corresponds to a current magnitude of 30 kA. At the time of peak output current (30 kA), there were 1,350 J stored in the inductor. From the full view of the  $dI/dt$  waveform the maximum current derivative value is seen as  $\sim 50$  kA/ $\mu s$ , accounting for slight clipping of the waveform. Roughly -150 kV is calculated using  $L_{Storage} * dI/dt_{max}$ . The high voltage probe did not measure any meaningful signal, and it was concluded that the peaking gap did not break down, so no voltage or dissipated energy values were measured from the 20  $\Omega$  load.





**Figure 5.** HFCG output  $dI/dt$  and current waveforms with fuse opening switch



**Figure 6.** The full  $dI/dt$  magnitude, slightly clipped on the lowest point of the waveform.

This generator was seeded with 6 kA and 90 J of energy into the 5  $\mu$ H dynamic transformer primary. 1,350 J was the expected output energy value since the HFCG was seeded with relatively low energy (energy amplification at the time of switch opening is  $\sim 15$ ). Even with an output energy level of 1,350 J, the calculated open circuit voltage reaches -150 kV. Seeding the generator with more energy will produce larger current and energy magnitudes at the output of the HFCG, resulting in a higher voltage amplitude. It is expected that the voltage across the resistive load will be in excess of 150 kV with increased seed current and an optimized fuse.

#### IV. CONCLUSIONS

These tests show that the present HFCG design consistently delivers current magnitudes in the 30-45 kA range to the energy storage inductor when seeded with a current of 6-8.5 kA. Load energy levels ranged from 1,300-3,000 J, also depending on seed energy. Using the generator performance characteristics, the exploding wire fuse was designed to operate optimally in this range of current magnitudes. The fuse performance measurements show that the generator and power conditioning system are easily capable of producing a 150 kV pulse. As stated previously, 30 kA is a low output current magnitude for

this generator design. When seeded with more energy, the generator is expected to produce voltage magnitudes greater than 150 kV across the 20  $\Omega$  resistive load. While the shot to shot generator performance statistics have been consistent for shots with no waveform anomalies, more data must be taken with the fuse system before a complete conclusion can be reached on the HFCG and power conditioning system's ability to drive a load with impedance values in the tens of ohms.

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